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8 Congestion Management and Loss Optimization with FACTS

This chapter focuses on power flow controlling FACTS-devices and their benefits in market environments. These devices have a significant influence on congestion management and loss reduction. Especially the speed of FACTS-devices provides an additional benefit in comparison to conventional power flow control methods. However, to earn these benefits a special post-contingency operation strategy has to be applied which will be explained in this chapter.

The aim of this chapter is beside the analyses of the qualitative benefits as well to assess the quantitative economic benefits. In particular, we

- analyse under which conditions fast load flow controlling devices like DFC or UPFC allow for a reduction of total system cost,
- estimate the amount of this reduction exemplarily for a realistic scenario within the UCTE system.

In this chapter 'Load Flow Controller' (LFC) is used as a general term for power flow controlling devices like Dynamic Flow Controller (DFC), Unified Power Flow Controller (UPFC) and Phase Shifting Transformer (PST). The acronym DFC is used exemplarily for all kinds of fast and dynamic power flow controllers.

8.1 Fast Power Flow Control in Energy Markets

8.1.1 Operation Strategy

The liberalisation of electricity markets has led and continues to lead to an increase in volume and volatility of cross-border power exchanges. As a consequence, particularly the transmission networks are operated closer to their technical limits. At least indirectly, some of the numerous major blackouts of the recent years have been related to this development.

Beside strict regulations [1], there are several new technologies with the aim to enable transmission system operators (TSOs) to cope with these challenges by reaching optima in terms of maximum transmission capacity, minimum cost and ensuring of network security. Among the most promising of these innovations are FACTS-devices for power flow control such as DFC or UPFC.

Shifting power flows between areas of a power system means to deviate from the natural power flow. The target for doing this is to increase the power flow over a line or corridor with free capacity or to decrease the flow in an overloaded part of the system. The benefit is measured as increase of the total or available transfer capability (TTC or ATC), which considers the N-1-criteria. The drawback is normally increased losses in the system.

Traditionally the set values of power flow control devices, usually phase shifting transformers, are predetermined to be optimal for all expected contingencies. This means, that the maximum transfer for the expected most critical contingency is increased. The benefit is the difference $TTC_2 - TTC_1$ in Fig. 8.1. The system is prepared for this contingency, but it is running almost all the time in a non-optimal way according to losses or other criteria.

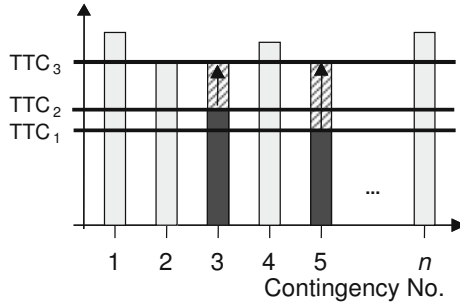


Fig. 8.1. Total Transfer Capability without (TTC_1), with PST (TTC_2) and DFC (TTC_3)

In comparison to this traditional approach, a fast controllable power flow control device opens up opportunities to change the set values within or even below a seconds time range to adapt to just occurring contingencies. The fast power flow control may, in principle, result in the following advantages for Transmission System Operators:

- Already during undisturbed network operation slow load flow controllers like PSTs have to be set such that after any contingency all technical quantities remain within their admissible limits. With a fast flow controller, the (N-1)-security criterion can also be fulfilled if after the contingency the DFC is shifted to relieve any overloaded transmission lines or transformers. Even for fast evolving instabilities the DFC is fast enough to reach a stable operation point. If the system has a certain overload capacity and a PST would in principle be fast enough, the DFC would provide more flexibility. The result is that the power system operates loss optimal most of the time. Only in emergency situations the DFC changes to a new set value according to the concrete contingency.
- With a preset target value - the usual operating practice with PSTs - one setting needs to satisfy all contingency situations. By using the DFCs' ability of fast, post-contingency switching, the amount and direction of load flow control can

be dynamically adapted to the actual location of the fault or the overloaded network element. Depending on the network and market conditions, this may enable TSOs to provide additional transmission capacity without compromising network security. Two contingencies, which would require contradictory control actions, can be handled with one device. In Fig. 8.1, contingencies 3 and 5 would require contradictory actions to increase the TTC value. The DFC adapts its action to the respective contingency just after its occurrence. This gives the additional benefit $TTC_3 - TTC_2$.

- Besides, power electronic devices allow for an improvement of network stability.

This chapter focuses on the first two benefits and shows how the reduction of losses as well as an increase of transmission capacity leads to a decrease of total system cost.

8.1.2 Control Scheme

Due to the wide-area influence that load flow controlling devices have on the transmission system, the practical realisation of the above advantages requires the provision and utilisation of distant wide area power, current and voltage measurements. In both cases of the previous section - loss reduction and transmission capacity increase - an automatic control scheme needs to be implemented. The time scales of changing the set values depend on which kind of stability boundary is limiting the transfer capability. In case of thermal limitations a certain overload over a couple of minutes can be accepted, but the speed of the action increases the flexibility to react on changing situations.

There are two principle options to automate the control scheme:

- The information on the most severe contingencies, for instance line outages, must be transmitted to the controller. The controller has a set of pre-defined post-contingency set-values, which are used according to the specific contingency. The calculation of these pre-defined values must be done frequently to be as accurate as possible to the actual situation.
- As an alternative, not the contingency itself, e.g. the outage of a line, is measured, but the effect on the parts of the system leading to the limitation. In this case, the flows on the parts or lines, which tend to be overloaded after the contingencies, need to be measured and transferred to the controller. The controller automatically controls the flow of the most critical line to its defined maximum.

In both cases the control scheme is based on rules, which guarantee well defined and unambiguous actions of the DFC (see as well chapters 10, 11 and 12). The second control scheme has the advantage of a higher accuracy, because the effect of the contingency is directly measured and no pre-calculated set-values are required except the maximum flows over the lines.

The required speed for the communication depends on the desired control

speed. The fastest and most accurate control system would be a wide area control system based on time-synchronized phasor measurements [2]. With such a system, specific algorithms to identify actual limitations of corridors or lines can be applied as input variables for the Dynamic Flow Controller [3]. Wide area control schemes for these applications will be discussed separately in chapter 12.

8.2 Placement of Power Flow Controllers

At first we investigate which fundamental prerequisites need to be fulfilled such that the DFC provides more transmission capacity than the PST. This analysis is done on the basis of simple four node networks. In a second step, we perform an exemplary quantification of the DFC's annual benefit for a realistic network scenario in order to verify the fundamental findings.

According to the basic approach from section 8.1, using a slow LFC means to have one tap position that meets all network constraints in all (N-1)-cases. Using DFC for each topology of the (N-1)-criterion separate tap positions can be used, which are applied in the post-contingency cases. When considering a single topology, there is in general a range of admissible tap positions. Only when the transmission volume and hence the loading of the network exceeds a certain level, the admissible tap range becomes empty, meaning that the slow LFC is no longer able to maintain network security.

Using a PST at least one common tap position needs to exist in all topologies. In other words, there must be a non-empty intersection of the admissible tap ranges. A DFC yields a benefit if a compromise between tap positions for different topologies is necessary. This is the case when for a higher transmission volume admissible tap ranges still exist for each topology, but no tap position can be found that is admissible for all topologies.

From this we can conclude that a benefit of a DFC compared to a PST can only be achieved if two requirements are fulfilled:

- two different (N-1)-topologies are limiting the transmission volume, not including the DFC outage,
- the DFC needs to have sensitivities with opposite signs on two 'limiting' lines (i.e. lines that are fully loaded in the critical topologies).

Therefore, the admissible tap ranges in the relevant (N-1)-topologies are the key measure to assess whether the DFC yields a benefit compared to the PST.

A four node network in Figure 8.2 with three lines in the prevailing transmission direction has been developed for the purpose of illustrating the principle of this approach. Power is injected at the lower three nodes and has its sink at the fourth node on top. With this network we have created three scenarios with different installations of LFCs. In the first scenario an LFC is placed crossways to the transmission direction between a double line and a single circuit.

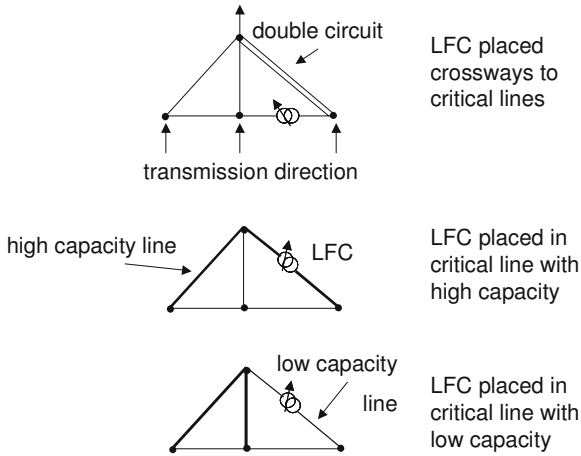


Fig. 8.2. Possible locations of LFCs - schematic illustration

In both remaining scenarios the LFC is installed in one of the lines in main transmission direction, with the difference that it is a strong line in the second scenario and a weak line in the third one.

In the first schematic network configuration shown in Figure 8.3 the LFC is placed crossways to critical lines, which satisfies the prerequisites of two limiting topologies not including the LFC outage and sensitivities with opposite sign on two limiting lines. In case of a line outage of the single line on the left the LFC would be used to relieve the central line, which is illustrated by an arrow. If one circuit of the double line trips, the LFC will aim at relieving the remaining circuit to prevent an overload.

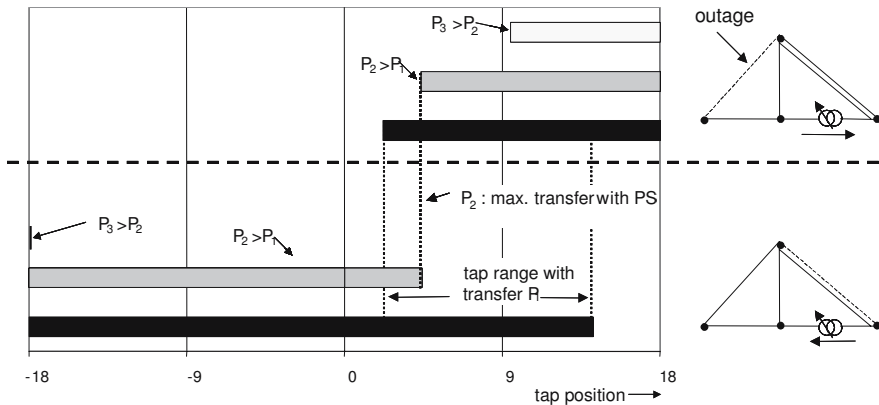


Fig. 8.3. Admissible tap ranges for two critical outages and varied power transfers – LFC placed crossways to critical lines

Hence, the circular flow injected by the LFC is in opposite directions for the two critical topologies. When using a PST a compromise between tap positions for these two topologies will be necessary which limits the amount of transfer. With low transfer P_1 the admissible tap ranges overlap and several common tap positions can be found that fulfil all network constraints (black bars in Fig. 8.3). When increasing the transfer the admissible tap ranges will shrink up to the point when they have just one single tap position in common (grey bars). The according transfer P_2 is the highest transfer that can be achieved using a PST. For any transfer higher than P_2 a DFC is required because the admissible tap ranges (white bars) have then become mutually exclusive. The maximum transfer P_3 is achieved when the DFC reaches its maximum or minimum tap setting for at least one of the critical topologies. The gain of transmission capacity by using a DFC instead of a PST is $P_3 - P_2$.

In the second schematic network configuration in Figure 8.4 the LFC is placed in a line with high transmission capacity. This means that the LFC contingency is among the critical contingencies. Hence, the resulting tap range is only relevant for a single critical topology, meaning that a PST is equivalent to a DFC.

To avoid the LFC being among the critical contingencies, it is now placed in a low capacity line while the two other lines leading to the sink node are strong ones in this scenario of Figure 8.5. However, in case of an outage the relief of critical lines is achieved by tap changing in the same direction for both topologies as it is indicated by the arrows in the Figure. Consequently, the admissible tap ranges always overlap, which means that again a DFC is equivalent to a PST.

Even a scenario with two LFCs, one in each strong line, can be traced back to a superposition of the previous two scenarios making a PST equivalent to a DFC.

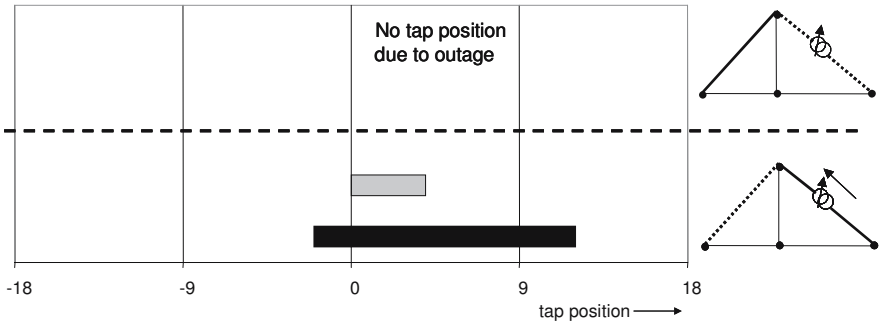


Fig. 8.4. Admissible tap ranges for two critical outages and varied power transfers - LFC placed in critical line with high capacity

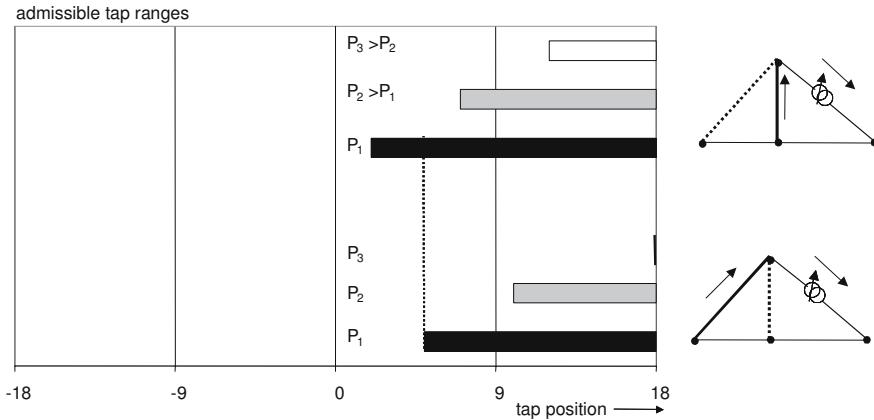


Fig. 8.5. Admissible tap ranges for two critical outages and varied power transfers – LFC placed in critical line with low capacity

The fundamental analysis on the basis of the schematic networks shows that an increase of transmission capacity can only be achieved under special circumstances. To achieve non overlapping admissible tap ranges the following conditions need to be fulfilled:

- DFC placed crossways to 2 critical lines, and
- two critical topologies exist excluding the DFC.

To confirm this conclusion under realistic UCTE network conditions an analysis of different DFC locations for an exemplary network situation has been carried out, which will be presented in section 8.4.

8.3 Economic Evaluation Method

Both advantages to be analysed - loss reduction and increase of transmission capacity - relate to the topic of cross-border congestion management, because this is the primary reason for the installation of load flow controlling devices. Therefore, we first discuss how to include load flow controllers in network models used for congestion management, in particular for the allocation of transmission rights.

8.3.1 Modelling of LFC for Cross-Border Congestion Management

Various different methods for the allocation of transmission rights have been implemented by the TSOs in recent years. In the EU this development has been accelerated by the coming-into-force of the related EC regulation 1228/2003 in mid-

2004 [1]. There is a clear tendency towards solutions that are based on intensified coordination among TSOs and between TSOs and other actors, with the aim of better utilisation of the network infrastructure. In the technical sphere, this can be achieved by using so-called Power Transfer Distribution Factor- (PTDF-) models to represent the transmission constraints [4]. The following method is based on such PTDF-models, for the following reasons:

- The analysis of the fundamental properties of LFCs should not be based on transitory arrangements (such as bilateral and/or non market-based allocation procedures for transmission rights in meshed grids) - also in view of the expected lifetime of these devices.
- Although the pace of further evolution of the actually applied congestion management methods is difficult to anticipate, it is obvious that methods based on PTDF-matrices are likely to become effective in the next years.

In this section, we first describe the basic properties of a PTDF-model and then discuss how 'slow' and 'fast' load flow controllers can be included therein.

8.3.1.1 Basic Network Model

The cross-border transmission capability of for instance the UCTE network is mostly restricted by the admissible line currents, which, given the relatively constant voltage level, can approximately be expressed in terms of active power flows.

The PTDF-model is based on a linearization of the steady-state load flow equations, which is valid with acceptable accuracy for the context of congestion management: The power flow on each transmission line (or transformer) has an approximately constant sensitivity with respect to the export/import balance of a given network zone (corresponding to a trade area, usually one TSO's control area). Therefore, the limited transmission capability of the network can be expressed through a set of inequalities that link the maximum admissible flow on the lines (or transformers) to the zonal balances:

$$\begin{array}{c} \text{zone 1} \quad \text{zone n} \\ \text{Topo. 1} \quad \begin{array}{c} \text{line 1} \\ \vdots \\ \text{line m} \end{array} \quad \begin{array}{c} \text{S} \\ \vdots \\ \text{S} \end{array} \\ \hline \text{Topo. 2} \quad \begin{array}{c} \text{line 1} \\ \vdots \\ \text{line m} \end{array} \quad \begin{array}{c} \text{S} \\ \vdots \\ \text{S} \end{array} \\ \text{sensitivity matrix} \end{array} \cdot \begin{array}{c} \text{zone 1} \\ \vdots \\ \text{zone n} \end{array} \left(\begin{array}{c} \Delta P \\ \vdots \\ \Delta P \end{array} \right) \leq \begin{array}{c} \text{line 1} \\ \vdots \\ \text{line m} \end{array} \left(\begin{array}{c} P^{\max} \\ \vdots \\ P^{\max} \end{array} \right) \quad (8.1)$$

The (N-1)-network security criterion can be reflected in the PTDF-model by computing the sensitivities for each contingency topology and combining the results to a large set of inequalities. This makes sure that a set of zonal balances (i.e. power exchanges between the zones) must not lead to a violation of line flow limits in any of the considered topologies.

8.3.1.2 Inclusion of 'Slow' LFC

In principle, load flow controlling devices have a similar effect on the network as the zonal balances: They alter the flow on the lines and transformers. It can be shown that this influence is also approximately linear, i.e. the incremental power flows due to tap changes of load flow controllers (LFCs) can be superimposed on those induced by the zonal balances, and they are proportional to the tap setting. (Note that we are using the term 'tap change' here and in the following, although power electronic load flow controllers can be designed such that they allow for continuous shifting. In the PTDF-model, this can be easily reflected by allowing the 'tap position' to have continuous values instead of integers in the case of conventional PSTs.) Consequently, the PTDF matrix needs to be extended by one column per LFC:

$$\begin{array}{c} \text{zone 1} \quad \text{zone n} \quad \text{LFC 1} \quad \text{LFC 2} \\ \text{Topo. 1} \quad \begin{array}{c} \text{line 1} \\ \vdots \\ \text{line m} \end{array} \quad \begin{array}{|c|c|} \hline S & S_{\text{tap}} \\ \hline \end{array} \\ \text{Topo. 2} \quad \begin{array}{c} \text{line 1} \\ \vdots \\ \text{line m} \end{array} \quad \begin{array}{|c|c|} \hline S & S_{\text{tap}} \\ \hline \end{array} \end{array} \cdot \begin{array}{c} \text{zone 1} \\ \vdots \\ \text{zone n} \\ \text{LFC 1} \\ \text{LFC 2} \end{array} \begin{pmatrix} \Delta P \\ \vdots \\ \Delta \text{tap}_{\text{LFC1}} \\ \Delta \text{tap}_{\text{LFC2}} \end{pmatrix} \leq \begin{array}{c} \text{line 1} \\ \vdots \\ \text{line m} \\ \text{line 1} \\ \vdots \\ \text{line m} \end{array} \begin{pmatrix} P^{\text{max}} \\ \vdots \\ P^{\text{max}} \end{pmatrix} \quad (8.2)$$

Like with the basic model, the integration of sensitivities for all contingency topologies ensures that one set of tap positions (and one set of zonal balances) satisfies all contingency conditions, thus reflecting properly the requirements of the 'slow' PSTs.

8.3.1.3 Inclusion of 'Fast' LFC

The difference between 'slow' and 'fast' LFCs is that the latter can be shifted to an individual tap position after each contingency. When modelling the network constraints, this means that each topology may have its individual set of tap settings. For example, tap settings applying to topology 1 have no effect in topology 2, 3 etc. This is reflected by blocks of zeros in the PTDF-matrix:

$$\begin{array}{c} \text{LFC 1, LFC 1, LFC 2, LFC 2,} \\ \text{topo 1 topo 2 topo 1 topo 2} \\ \text{zone 1} \quad \text{zone n} \\ \text{Topo. 1} \quad \begin{array}{c} \text{line 1} \\ \vdots \\ \text{line m} \end{array} \quad \begin{array}{|c|c|c|c|} \hline S & S_{\text{tap}} & 0 & S_{\text{tap}} \\ \hline \end{array} \\ \text{Topo. 2} \quad \begin{array}{c} \text{line 1} \\ \vdots \\ \text{line m} \end{array} \quad \begin{array}{|c|c|c|c|} \hline S & 0 & S_{\text{tap}} & 0 \\ \hline \end{array} \end{array} \cdot \begin{array}{c} \text{zone 1} \\ \vdots \\ \text{zone n} \\ \text{LFC 1} \\ \text{LFC 1} \\ \text{LFC 2} \\ \text{LFC 2} \end{array} \begin{pmatrix} \Delta P \\ \vdots \\ \Delta \text{tap}_{\text{LFC1}} \\ \Delta \text{tap}_{\text{LFC1}} \\ \Delta \text{tap}_{\text{LFC2}} \\ \Delta \text{tap}_{\text{LFC2}} \end{pmatrix} \leq \begin{array}{c} \text{line 1} \\ \vdots \\ \text{line m} \\ \text{line 1} \\ \vdots \\ \text{line m} \end{array} \begin{pmatrix} P^{\text{max}} \\ \vdots \\ P^{\text{max}} \end{pmatrix} \quad (8.3)$$

8.3.2 Determination of Cross-Border Transmission Capacity

Algorithms calculating bilateral cross-border transmission capacity as well as co-ordinated mechanisms for multi-zone capacity allocation determine the maximum

cross-border power exchange that is admissible within the limitations imposed by the transmission network. Mathematically, this can be expressed as an optimisation problem in which the PTDF-model constitutes the principal part of the constraints. A comparison between PSTs and DFCs can then be achieved by simply switching between the models described by equations (8.2) and (8.3), respectively.

The specification of the objective function reflects the context of exchange maximisation (e.g. bilateral capacity calculation, co-ordinated explicit auctioning or implicit auctioning). For this study, two methods are appropriate, depending on the focus of the investigations:

- For the increase of transmission capacity by DFC in comparison to PST (section 8.2), the amount of power exchange in a fixed direction (e.g. from country A to country B) forms the objective function. This means that the zonal balance in A contributes positively and in B negatively to the objective function, whereas all other balances are set to zero. Optimisation variables are the zonal balances and the LFC settings. Such a procedure is based on the assumption that (in a given trading interval) the regarded power transfer direction is economically beneficial. This allows to isolate the effect of having either fast or slow LFCs and avoids confusion by superposition with interdependent effects that are difficult to trace in detail.
- In a market with several trading zones, the most beneficial transfer direction is volatile. Moreover, there might be interdependency between the optimal transfer direction and the PTDF-model variant for PST or DFC. Therefore, the estimations of loss reduction as well as of the economic welfare gain through LFCs are carried out without prescribing such a direction. Rather, the zonal balances are a result of the variable unit commitment, and the LFCs' tap positions are used as degrees of freedom in an optimization with the objective function of minimal total generation cost. The methods used for these analyses besides the PTDF-model are described in the following section.

8.3.3 Estimation of Economic Welfare Gain through LFC

Severe transmission congestions have occurred since the liberalisation of the electricity supply sector as a consequence of increasing cross-border power transfers. The congestion hinders free energy trades and leads to different regional electricity prices at the national power markets. In an ideal market, the economic benefit of additional transmission capacity is determined by the reduction of generation costs due to an additional power transfer from the area with lower marginal costs into the area with higher marginal costs of generation. The associated costs of additional transmission capacity consist of investment and maintenance costs of network reinforcement, as well as costs of network losses. The maximum of social welfare can be reached by maximising the difference between the benefit and the associated costs.

In the following the reduction of generation costs due to an increased transmission capacity is estimated applying a market simulation based on a generation dispatch model. This model optimises generation plant dispatch and transmission capacity usage by minimising total generation costs in the system. A part of the UCTE system is considered for which the model comprises major Western European countries. On the generation side, the thermal and hydro generation as well as the wind power injection are considered. The transmission network including LFCs is modelled as linearized transmission constraints (see section 8.3.1).

Fig. 8.6 shows an overview of the developed methodology to evaluate the benefit of LFCs. The influences of LFCs on the transmission capacity and thus the generation dispatch are quantified by the market simulation. Hourly unit commitment, generation costs, cross-border energy exchange, as well as the setting of LFCs are the essential results of the market simulation. With this information a load flow calculation can be carried out to compute the corresponding hourly network losses.

This procedure shall be done both for conventional PSTs and for the fast DFCs. Finally we can compare the change of generation costs, as well as of network loss cost.

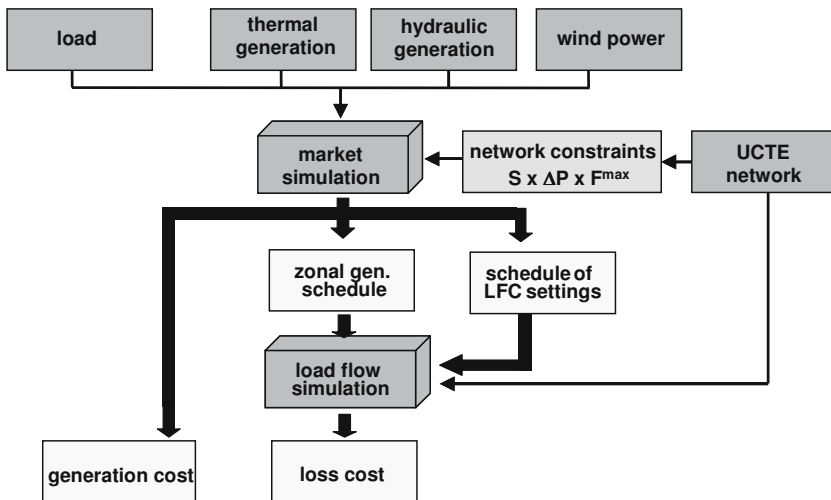


Fig. 8.6. Overview of the methodology applied to quantify the economic welfare gain through DFCs

8.3.3.1 Generation Cost - Market Simulation

Owing to the problem size the optimisation is solved by linear programming. The objective function represents minimisation of variable generation cost to cover the load in the entire system. Besides the hourly output of generation units, the setting

of LFCs is a part of the optimisation variables, too. The optimisation constraints consist of technical properties of power plants, transmission network restrictions and many other technical conditions, such as load balance and system reserve requirements.

The generation dispatch model uses the system marginal cost as the price estimator. The electricity price in a perfectly competitive market shall be equal to the system marginal cost at all times. In a market with only a few players, electricity prices are subject to the strategic behaviour of dominant market participants. In this case, electricity prices can be raised above the system marginal cost. While this market power phenomenon is more or less evident in a number of European regional markets today, it can be expected to be mitigated in the medium term as a consequence of efforts by the European Commission, the national regulators and other stakeholders. For example, mitigating market power is one of the main goals of improving congestion management methods in the European transmission system [4]. Hence we can expect that market prices will tend to approach the marginal cost level in the future. Besides, a simulation based on marginal cost minimisation is ideal to reveal the socio-economic welfare gain that could be achieved by DFCs.

While the cross-border transmission capacity often limits the international power transfers, the power grids inside a country are usually strong enough to support free power transfers within the country. Although this is not always exactly the case, the continental European market is structured such that in most countries unlimited domestic transmission capacity is assumed. This means that any internal congestion is managed by corrective re-dispatching measures, whereas ex-ante restrictions of inter-regional power exchanges are only imposed on an international scale. Corresponding to this situation, each national market is modelled as a trade zone in the generation dispatch model. Within a trade zone the whole generation system is directly coupled with the aggregated load on a fictive lossless hub, thus the internal power flows are neglected. The trade zones are interconnected through the transmission network with limited capacity. The load flow behaviours and the transmission constraints are modelled as described in section 8.3.1, based on the assumption that step by step a multilaterally coordinated allocation of transmission rights will be implemented in the European Union in the future.

The generation model uses detailed information about generation systems and the interconnected transmission network of seven Western European countries: Austria, Belgium, Switzerland, the Netherlands, Germany, France and Italy (Figure 8.7). The Netherlands and Belgium are merged to one region in order to save computing time, as network congestion between these two countries seems to be quite rare, according to transmission capacity auctioning results.

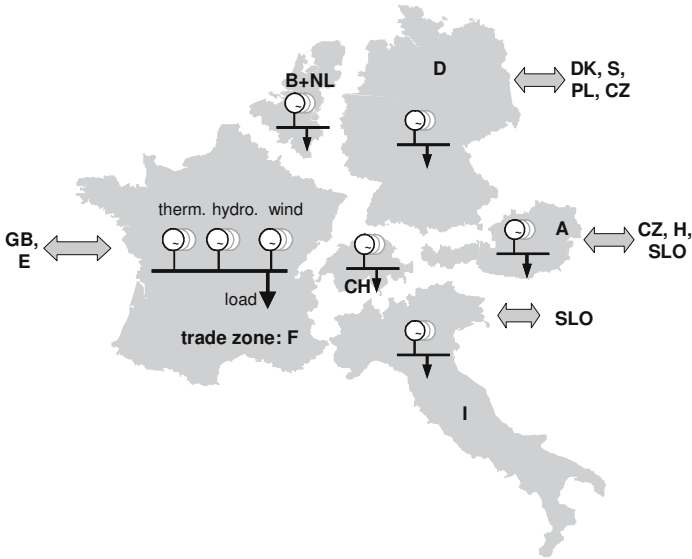


Fig. 8.7. Countries considered in the market simulation

The surrounding countries - Spain, Great Britain, the Scandinavian countries as well as the Eastern European countries - are not modelled in detail. Their interactions with those countries that are modelled in detail are considered as predefined power exchange schedules.

Exogenous inputs such as load curves, fuel prices, available generation capacities and the transmission network aim at mirroring the situation of year 2003. All input data have been taken from public sources. For simplification a single network topology is used for the entire year, which is sufficient to show under which circumstances DFCs can have advantages compared to conventional PSTs. As we are interested here in a comparison between new DFCs and conventional PSTs, not the absolute value, but only the differences of simulation results are considered, which reduces further the impact of inaccuracies of the input data.

8.3.3.2 Loss Cost – Load Flow simulation

As mentioned above, the investigation is based on a single load flow dataset drawn from public sources. In order to calculate the transmission losses it is necessary to update this load flow model according to the hourly market simulation results.

These results contain the aggregated generation and load within each trade zone for each simulated point of time. To update the load flow model the deviations of these zonal values from the base case are distributed to all the generation units and loads proportional to their power injection/take-off in the base case. This constitutes a decoupling of the market simulation model and the load flow model.

The transmission constraints in all relevant (N-1)-situations are considered in the market simulation. However, because of the short duration of post-contingency situations only the normal network topology is used for load flow calculation. Hence, the yearly transmission losses are determined by adding up the transmission losses obtained from one load flow calculation for each simulated point of time.

The comparison between the influence of DFCs and PSTs on the transmission losses is achieved by considering that they may be set to different tap positions during undisturbed network operation.

8.4 Quantified Benefits of Power Flow Controllers

8.4.1 Transmission Capacity Increase

As a scenario we have selected the European region around Belgium, the Netherlands and Luxembourg. The reason is on the one hand the actual presence of congestion and on the other hand the fact that there are already LFCs in operation at two substations (Meeden and Gronau) at the Dutch-German border. Figure 8.8 gives an overview of the principal transmission lines in that area. A more detailed description of the congestion situation can be found in [5].

Before performing the one year market simulation to estimate the economic benefit an appropriate location for the DFC needs to be identified. Today the existing PSTs in the considered Benelux region are placed in tie lines, so we considered first DFCs as replacements for the existing PSTs at the Dutch-German border. As result of the fundamental analysis in section 8.2 the use of DFCs for transmission increase in a tie line is unlikely to provide a benefit towards PSTs.

For the part of UCTE-system a location for a DFC to increase the transmission capacity more than a PST could only be found under some specific network development assumptions. We had to reduce the thermal limits of the double circuit Vigy-Uchtelfangen by 40 % to make it a critical line. Also neglecting limitations of 220-kV-lines (e.g. tie line Moulaine-Aubange) was necessary. The DFC and in comparison the PST is placed in the branch Vigy-Moulaine.

For the analysis we first regard a single network situation and a fixed transmission direction from France to Belgium/Netherlands (BNL). This is equivalent to calculating the available transfer capacity (ATC) from France to BNL. In this modified scenario BNL imports 3900 MW with 200 MW remaining import capacity from France to BNL without any LFCs. By installing a PST a total import of 4300 MW can be achieved. Considering a DFC we have evaluated a maximum power import of 4700 MW which gives an additional benefit of 400 MW by the speed of the device. The result of the tap calculation is shown in Figure 8.9.

The next step is to determine how often this benefit is achieved during a year and what total profit will be gained. Therefore we perform a one year market simulation for this network situation.

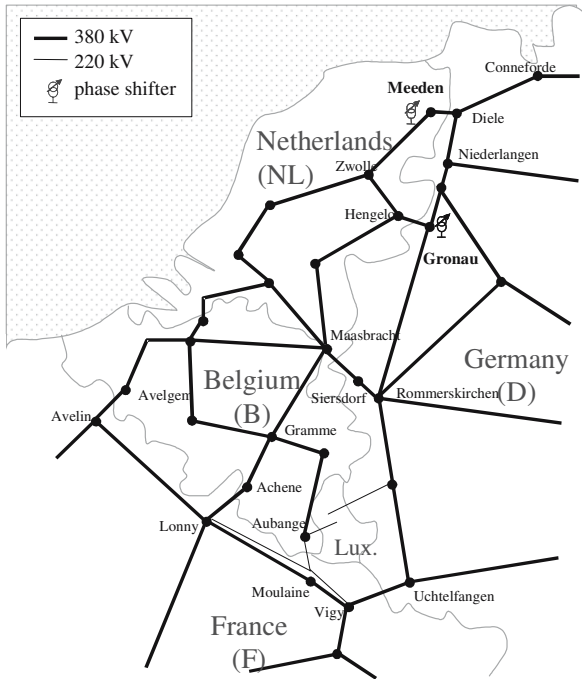


Fig. 8.8. Overview of the transmission network in the vicinity of Belgium and the Netherlands

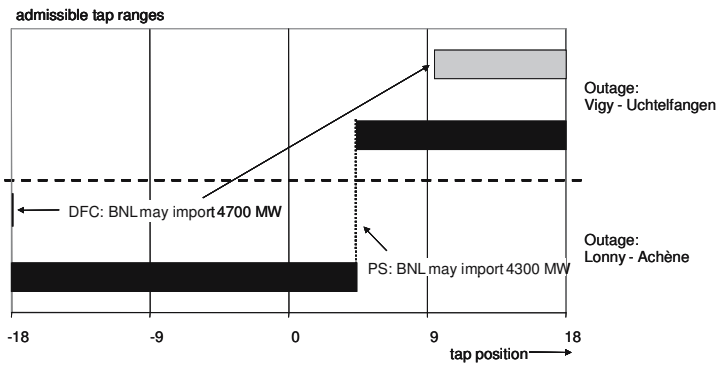


Fig. 8.9. Admissible tap ranges for two critical outages and varied power transfers - DFC placed crossways to critical lines

The simulation results of Figure 8.10 show that total generation cost can be reduced by 3.8 Mio. €/a. The comparison between the DFC and the PST simulation show that a variation of cross-border power exchange occurs in 53 % of the time slots. As a consequence of the inter-temporal couplings due to the hydro power plants, both positive and negative variations occur. Over all time slots with variations of power exchanges, the average increase (i.e. the net sum of increases and decreases) of the cross-border transmission volume is slightly above 200 MW, and the average price difference between exchanging market zones is 3.76 €/MWh.

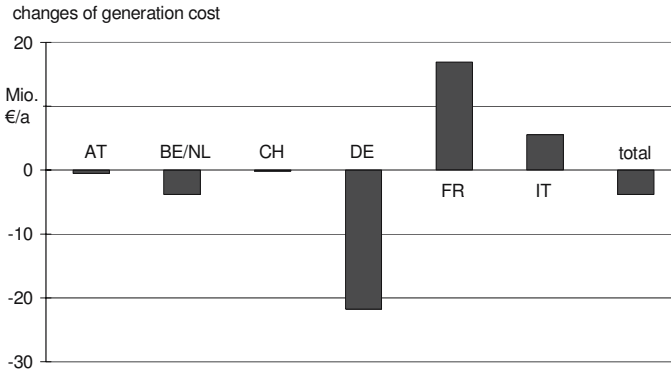


Fig. 8.10. Changes of generation cost through DFC in comparison to PST – Scenario: Reduction of thermal limit on Vigy-Uchtelfangen, neglect of 220-kV-limitations, DFC/PST placed in branch Vigy-Moulaine

The simulation also shows that the changes of generation cost are quite different in the affected countries. France for example bears an increase of generation cost caused by a higher amount of power export. On average this would also result in higher marginal cost in France, since it is likely that at least during some hours of the year the increased amount of generation requires to operate significantly more costly generators. So only some countries earn a 'local' benefit from the DFC installation, but in total a socio-economic benefit can be achieved for this fictitious scenario.

8.4.2 Loss Reduction

Because of their fast controllability DFCs allow to react to a contingency after its occurrence. This means that the natural load flow can be maintained throughout most of the time by operating in 'neutral' and loss optimal position during undisturbed network operation. In contrast to that the schedule of PST settings must be followed in all network situations according to the most critical contingencies which might come. From this difference a reduction of network losses can be assumed.

With the model that has been introduced in section 8.3.3 a simulation of an ideal market is carried out taking into account load and generation as well as the

UCTE-network with its constraints (Figure 8.11). Load flow calculations are performed determining the loss cost regarding the zonal generation schedule and the schedule of LFC-settings resulting from the market simulation. The comparison between the utilisation of DFCs or PSTs for load flow control is achieved by following the schedule of hourly post-contingency tap settings (PST) or maintaining the neutral setting (DFC), respectively.

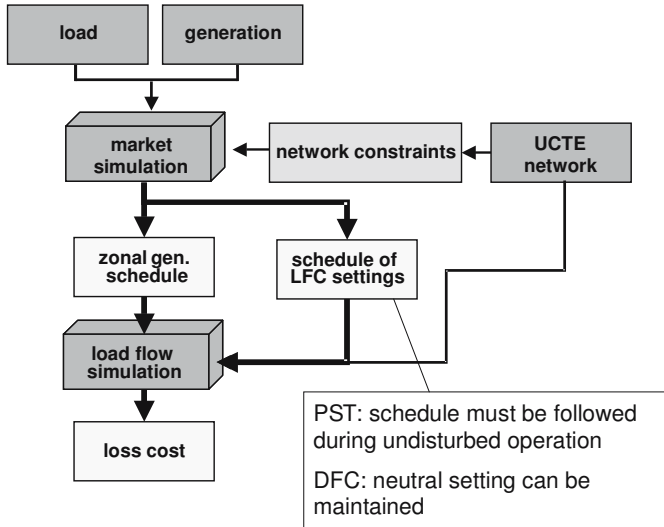


Fig. 8.11. Methodology for determination of loss reduction by using DFC instead of PST

Strictly speaking, the loss-minimal tap setting can, depending on the network situation, differ from the neutral setting. This would mean that, in theory, also the DFC would have to follow an hourly schedule. In order to assess the relevance of this aspect for the comparison between DFC and PST, we first perform a sensitivity analysis regarding the dependency of transmission losses on tap positions of PSTs in the two locations Gronau and Meeden.

We first regard the level of transmission losses for 2 exemplary load situations (Figure 8.12, curves, right axis). While the loss minimal tap position is zero or near zero in both peak load and off-peak situations, maximum losses occur at the lower and upper boundary of the tap range.

A subsequent one year market simulation identifies market optimal tap positions at the lower boundary of the tap range in most of the hours (Figure 8.12, columns, left axis). In comparison to the difference of the incremental losses between loss minimal and market optimal tap positions, the difference of incremental losses between the two loss minimal tap positions (peak and off-peak) is almost negligible. Therefore, neutral setting (i.e. a tap position of zero) is an adequate assumption for the default DFC-setting in undisturbed operation.

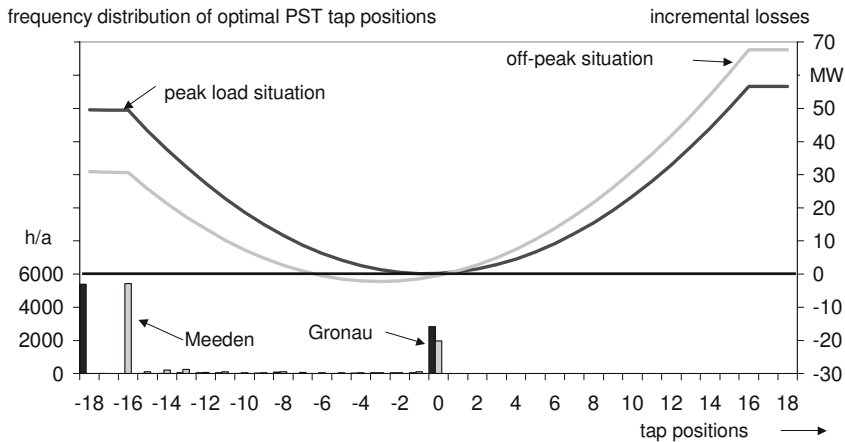


Fig. 8.12. Dependency of transmission losses on tap positions in Gronau and Meeden (curves, right axis) and comparison with distribution of tap positions resulting from market simulation (columns, left axis)

It is not certain that TSOs will use an LFC exclusively for increasing transmission capacity. For instance, a part of the tap range could be reserved for emergency actions. In order to account for this uncertainty, we have determined the yearly loss reduction for different restrictions on the share of the tap range to be used for capacity increase. For the monetary assessment we have assumed a loss price of 34 €/MWh, taken from European Energy Exchange (EEX) in November 2004 as the average price for base load for 2005 and 2006.

With full admissible tap range (i.e. the entire tap range is used for capacity maximisation) the loss reduction is 265 GWh/a, which constitutes a monetary benefit of 9.0 Mio. €/a with our assumption of 34 €/MWh. Yet, the simulation results also indicate a strong dependency of the loss reduction on tap range restrictions (Figure 8.13): For example, a bisection of the admissible tap range results in a decrease of the loss cost reduction by 80 %, meaning a drop to 1.8 Mio €/a in monetary terms. Obviously the uncertainty which share of the maximum tap range will be used by the TSOs has a significant influence on the profitability of DFCs. Figure 8.13 also shows a break-down of the loss changes per country. In the considered scenario the complete loss savings are gained in the zone Belgium/Netherlands (BNL), whereas all other zones will get a (smaller) increase of losses. We assume, however, that this finding cannot be generalised, but is depending on the specific scenario and might also be affected by the inevitable roughness of the simulation models.

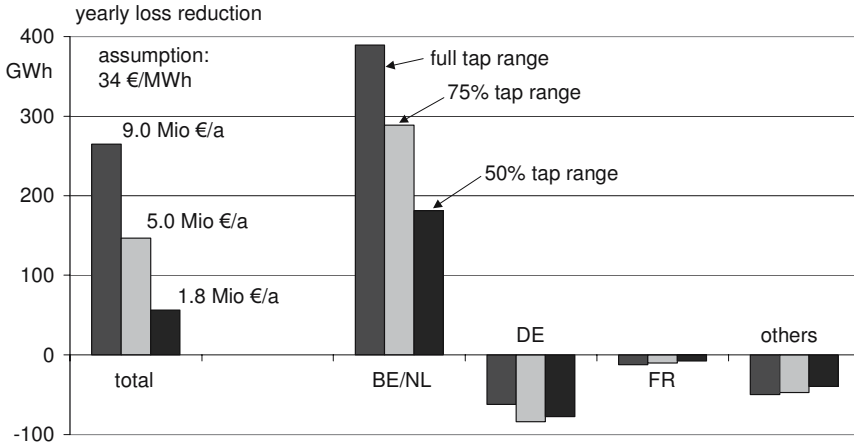


Fig. 8.13. Yearly loss reduction through DFCs (instead of PSTs) in Gronau and Meeden for different tap range restrictions

The energy market simulations of real situations in the European UCTE-systems quantify the benefits of the DFC in comparison to the PST. The control speed can primarily be used to reduce the system losses by operating in normal conditions according to optimal losses and adapt the operational point only in case of a contingency. The benefit in the case shown here was up to 9.0 Mio. €/a. This means that the dynamic capability would justify roughly a double price for the DFC in comparison to a 1000-MVA-PST with a payback in one year.

The first case for transmission capability increase has shown significant benefits only under special assumptions. The selection of a location where contradictory control actions are required might only occur in situations where the market actions change the power flow direction over the interconnection.

In conclusion, with specific operation strategy and placement significant benefits can be achieved by using fast controllable FACTS-devices in comparison to conventional power flow controllers. The capability for stability increase was neglected so far and will be discussed in the following two chapters. After that in chapters 10 to 12 a complete control scheme will be defined enabling to earn the benefits shown here.

References

- [1] European Parliament and Council of the European Union, "Regulation on conditions for access to the network for cross-border exchanges in electricity" Regulation (EC) No 1228/2003 of 26 June 2003, Official Journal of the European Union, L 176/1, 15 July 2003

- [2] Larsson M, Rehtanz C, Westermann D (2004) Improvement of Cross-border Trading Capabilities through Wide-area Control of FACTS. IREP Symposium, Bulk Power System Dynamics and Control VI, Cortina D'Ampezzo, Italy
- [3] Larsson M, Rehtanz C, Bertsch J (2003) Monitoring and Operation of Transmission Corridors. IEEE Bologna Power Tech, Italy
- [4] Consentec and Frontier Economics (2004) Analysis of Cross-Border Congestion Management Methods for the EU Internal Electricity Market. Study commissioned by the European Commission, DG TREN, Final Report, Aachen/London (available at www.consentec.de)
- [5] IAEW and Consentec (2001) Analysis of Electricity Network Capacities and Identification of Congestion. Study commissioned by the European Commission, DG TREN, Final Report, Aachen (available at www.consentec.de)